1998

THE EFFECTS OF ROCKET MOTOR OPERATING CONDITIONS ON EXHAUST PLUME SOOT CONCENTRATIONS

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Sponsor: Air Force Research Lab/Philips

OBJECTIVE: To obtain the optical properties, physical size, and mass loading of soot present in a liquid-fuel/gaseous oxygen rocket engine operation at fuel rich conditions and evaluate the effects of additives on those properties.

SUMMARY: The investigation succeeded in the development and operation of a liquid-fueled rocket engine with uniform exhaust soot loading under fuel-rich conditions. A multiple-wavelength extinction technique was used to obtain the optical properties of the soot. The transmission measurements and obtained optical properties were then used in conjunction with a thermodynamic equilibrium code to determine the overall soot loading in the exhaust.

OPERATIONAL REQUIREMENTS FOR LIQUID-FUELED PULSE DETONATION ENGINES

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Sponsor: Office of Naval Research

OBJECTIVE: To determine the atomization and mixing requirements for a liquid-fueled/gaseous oxygen pulse detonation engine combustor.

SUMMARY: Various atomization systems were analyzed to determine the droplet diameter distribution produced under transient injector operation. Injectors producing the smallest droplet diameters while maintaining the required fuel flow rates were then inserted into a variety of combustor geometries. The geometries were then evaluated to determine which resulted in the most successful operation over a predetermined equivalence ratio.

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D.W. Netzer, Professor
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Sponsor: Naval Air Warfare Center Weapons Division

OBJECTIVE: To determine the effects of geometry on the flow and mising characteristics of FASTHAWK combustors.

SUMMARY: A water tunnel study was conducted in support of the FASTHAWK combustor design. Five combustion chamber configurations (including a combustion can, aerogrid, turbulator and swirl devices at the dump plane) were evaluated with laser Doppler velocimetry to measure profiles of turbulence intensity and axial velocity. Laser sheet flow visualization was used to analyze flow patterns of seven different combustion can designs and nozzle exit swirl. The baseline, swirl, and aerogrid configurations produced similar flow characteristics, moderate turbulence intensity and a large primary recirculation zone. The latter was unsuitable for short (L/D<1.0) combustors. The combustion can and turbulator configurations were similar to one another with respect to axial velocity profiles and both produced a primary recirculation zone with L/D significantly less than 1.0. The turbulator configuration also produced significantly higher turbulence intensities throughout the combustion chamber, greater than any of the other configurations. The evaluation of the combustion can designs revealed the greatest impact on flow patterns results from the axial location of hole rows and that fuel injection is optimum when done near the downstream end of the primary recirculation zone.

D.W. Netzer, Professor
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Sponsor: Naval Air Warfare Center Weapons Division

OBJECTIVE: To measure the evaporation constant and buring characteristics of high energy-density liquid and slurry fuels.

SUMMARY: The measurements are to be made in 1997.

AFTERBURING SUPPRESSION

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Sponsor: Office of Naval Research and the Naval Postgraduate School

OBJECTIVE: To quantify the effects of solid propellant rocket motor exhaust particulates and nozzle geometry on the suppression of plume afterburning and to obtain effective nozzle geometries which do not adversely effect thrust.

SUMMARY: Experimental investigations were conducted to determine the expected behavior of burning aluminum droplets in rocket motors and the effects of particle loading and nozzle shapes used for enhanced plume mixing on the plume particle size distribution. Burning large aluminum particles, free-falling with gravity acceleration at atmospheric pressure will usually break up or shed lobes during or at the end of burning to produced multiple aluminum oxide fragments with diameters between 10% and 40% of the initial diameter. Single-particle and ensemble measurements in the plume were made using a micromotor mounted on a thrust stand. For both minimum-smoke and highly aluminized propellants the larger particles are concentrated along the plume centerline, in qualitative agreement with code predictions which treat nozzle flows without particle breakup or collision coalescence. For these propellants enhanced mixing nozzle shapes were found to increase the maximum particle size that is distributed throughout the plume from approximately 3μm to 5-6μm. Nozzle geometries were designed which were effective for reducing afterburning without significant thrust degradation.

1995

THE EFFECTS OF PARTICULATES ON SUPERSONIC SHEAR LAYERS AND AFTERBURING IN FUEL-RICH PLUMES

D.W. Netzer
Department of Aeronautics and Astronautics
Sponsor: Office of Naval Research

OBJECTIVE: To quantify the effects of solid propellant rocket motor exhaust particulates and motor operating conditions on supersonic shear layers, the effectiveness of mixing enhancement techniques and the resulting afterburning.

SUMMARY: Three techniques for enhanced mixing in supersonic plumes were investigated; nozzle exit tabs, annula cavities at he nozzle exit and a lobed nozzle. The effectiveness of the devices for significantly changing the extent of afterburing was first evaluated by exhausting hot, fuel-rich, supersonic gaseous flows into the atmosphere and recording the plume temperature distribution using a thermal imaging camera. Laser-sheet flow visualization ws also used to examine the resulting effects on the mixing and/or jet spreading rate. The devices were then used in an exhaust nozzle of a rocket motor that utilized both a highly aluminized propellant and a minimum-smoke propellant to determine whether or not the particulate affect the mixing process/afterburning. The exit tabs and lobed nozzle were found effective for changing the afterburning structure under the high exit Mach number conditions typical of tactical motors. Malvern mesurements across the plume showed that most of the volume (mass) of particulate was in particles with diameters between 4 and 5.5 microns. However, practically all of the number of particles had diameters smaller than 1.9 microns. A phase-Doppler particle analyzer (PDPA) in conjunction with multiple-wavelength extinction measurements were also used in a specially designed particle collection probe. The PDPA and Malvern measured distributions agreed in the observed modes near 1 and 4.5 microns. Scanning electron microscope pictures of collected particles were in good agreement with the measured Malvern Sauter mean diameter of 2.6 microns. Less than 3% of the total mass of particulates was found to be contained in particles with diameters less than 0.5 microns. Therefore, PDPA measurements alone can be used to determine the particle size distribution with good accuracy. The generation of axial vortices in the supersonic shear layers at the nozzle exit of rocket motors operating with characteristically high exit Mach numbers and temperatures can enhance the mixing rate and affect the afterburning for gaseous flow. Initial data have shown that the presence of large quantities of small particulate in the plume may significantly change the results obtained using enhanced mixing devices.

DESIGN AND DEMONSTRATION OF A SMALL, LOW-COST SUPERSONIC MISSILE FOR LETHAL UAV AND HELICOPTER APPLICATIONS

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Sponsor: Ballistic Missile Defense Office

OBJECTIVE: To determine the feasibility of a small, low-cost, caseless, hybrid-booster/solid-fuel ramjet sustain missile propulsion system that utilizes a common fuel grain and has no ejectables.

SUMMARY: Performance of an air-to-ground missile with a solid propellant booster and solid fuel ramjet (SFRJ) sustainer, capable of being fired from an unmanned aerial vehicle or helicopter was obtained using an Air Force/JANNAF computer code. A hybrid booster/SFRJ (H/SFRJ) sustainer motor was then designed analytically and compared to the generated computer output. The results showed that a H/SFRJ that has performance equal to a solid-booster SFRJ is feasible. The final missile design had a range of 20 nm, a flight Mach number of 2.0, a diameter and length of 5 and 99 inches respectively, and weighted 82 pounds. Caseless hybrid rockets with erodible nozzles were tested to validate assumptions made in the design analysis. In addition, transition from hybrid-rocket booster to solid-fuel ramjet sustainer was demonstrated.

PERFORMANCE OPTIMIZATION FOR LIQUID-FUEL RAMJETS

D.W. Netzer
Department of Aeronautics and Astronautics
Sponsor: Naval Air Warfare Center Weapons Division

OBJECTIVES: To determine optimum inlet dump configurations with and without the use of aerogrids. To evaluate the combustion characteristics of new, high energy-density fuels and fuel additives.

SUMMARY: Four variations of a single-side inlet-dump ramjet combustor were examined using laser Doppler velocimetry and laser sheet flow visualization in a water tunnel. Aerogrids were found to reduce the size of recirculation zones, eliminate the large-scale vortices shed from the inlet dump and increase fine-scale mixing. These effects should result in increased combustion efficiency and minimum combustion instability, but at the expense of narrower flammability limits and increased pressure losses. Two different scalloped inlets were investigated for providing the benefits of the aerogrid with reduced disadvantages. A geometry which produced high-amplitude, low frequency flow structures showed promise but further optimization is required. The burning rates and characteristics of several high energy liquid fuels, including JP-10, rj-7, Mobile E-5 and JP-8, and of high-octane, high flash point solvents were determined using a windowed combustion bomb at pressures from 1-10 atm, a video camera and a frame grabber. Atomization characteristics were measured using a poppet atomizer and a Malvern particle analyzer. Mobile E-5 and RJ-7 had higher burning rate and higher volumetric heating rates than JP-10. The solvents had adequate burning rates, but increased sooting characteristics due to high C/H ratios. Smoke suppressant additives may improve the

overall performance of these solvents. 0.6% by volume of an inexpensive, commercially available fuel additive in kerosene was found effective for reducing plume IR signature in a motor burning kerosene and oxygen. At an equivalence ratio of 2.0 and a pressure of 1.4 MPA the plume soot concentration was reduced by 65% and the average plume radiance by 82% in the 3.5-5μ band. The size distribution and optical properties of the soot were not significantly altered. Combustion efficiency was maintained between 93-96%.

MEASUREMENT OF SOOT EMISSIONS

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Sponsor: Naval Air Warfare Center Aircraft Division

OBJECTIVES: Adapt an existing three-wavelength laser extinction measurement system for use with a phase conjugate crystal to minimize atmospheric and beam steering effects on soot mass concentration measurements. Use the instrument in conjunction with a recently NPS developed soot mass concentration measurement technique to measure the soot concentration in simulated engine plumes.

SUMMARY: An instrument was developed and calibrated which is capable of on-line determination of soot concentration in plumes. The instrument utilizes an argon-ion laser, four passes through the exhaust plume using a retroreflector and a phase conjugate crystal to correct for aberrations in the transmitted beam and to increase accuracy when used in low opacity plumes. Several aspects of instrument layout and performance were investigated, and an initial calibration was performed using an ethylene-air combustor. The method requires further development, but shows significant promise for use in a jet engine test cell.

1994

COMBUSTION BEHAVIOR IN AIRBREATHING MISSILES

D.W. Netzer, Professor of Aeronautics and Astronautics

Sponsor: Naval Air Warfare Center Weapons Division

OBJECTIVE: To determine a liquid-fuel ramjet combustor geometry which can provide high combustion efficiency with combustion stability over wide operating limits.

SUMMARY: In FY93 three inlet-side-dump ramjet-combustor geometric configurations were investigated using non-intrusive water-tunnel flow visualization techniques to qualitatively determine optimum flame-stabilization dome lengths and fuel-injection locations and to investigate whether new configurations may be more capable of providing high combustion efficiencies under wide operating limits. Based upon the flow visualization results a dual, axially-in-line, side-dump, liquid-fueled ramjet combustor was designed and tested. Particle size distributions from the fuel atomizers were measured both in ambient conditions and under hot-air, contra-flow engine conditions. Data obtained under ambient conditions were found to have little value of the engine flow environment. The dual, axially-in-line geometry provided improved flammability limits and combustion efficiency at lean fuel-air ratios. Direct fuel injection into the recirculation zone was required for sustained combustion at lean equivalence ratios for the single side-dump configuration, but not for the dual in-line configuration. The fuel distribution in the inlet duct that was required for good flammability limits and combustion efficiency was opposite to that required to prevent pressure oscillations. A dump angle of 45^{o} resulted in lower than desired combustion efficiencies, apparently due to poor mixing from the aft inlet.

MEASUREMENT OF SOOT EMISSIONS FROM GAS TURBINE ENGINES

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Sponsor: Naval Air Warfare Center Aircraft Division

OBJECTIVE: To adapt a three-wavelength laser extinction measurement system with a retroreflector or equivalent for measurements of plume soot size and concentration. To compare results from a newly developed direct soot concentration measurement technique to those obtained using assumed soot optical properties.

SUMMARY: An apparatus was developed for determining soot particle densities by measuring laser light extinction through an exhaust plume. A two-pass technique with both a retroreflector and an optical phase conjugator crystal has been utilized. Although the conjugator returned the laser beam, showing proof of principle, a portion of the beam was not received back at the photodetector.

MEASUREMENT OF PARTICULATE AND PLUME CHARACTERISTICS FOR SOLID PROPELLANT ROCKET MOTORS

D.W. Netzer, Professor of Aeronautics and Astronautics

Sponsor: Air Force Phillips Laboratory

OBJECTIVE: (1) To upgrade an existing combined optical/collection probe for plume particle size measurements by replacing an ensemble particle sizer with a phase-Doppler particle analyzer (PDPA) in conjunction with multiple-wavelength extinction measurements. (2) To determine if alternative fuels can be used to reduce plume IR signature without significant effects on motor performance. (3) To examine the effects of nozzle residence time on the plume particle size distribution.

SUMMARY: Prove/PDPA data obtained in the plume on the nozzle centerline and radially displaced, Malvern data obtained across the entire plume width and multiple-wavelength extinction measurements in the plume edges show that the size distribution changes rapidly with plume radius. D_{32} decreased from approximately 18μ on the centerline to < 0.3μ in the plume edge and was 1-5μ when measured across the whole plume width. At the nozzle exit, D_{43} was 1.2-12μ (but typically 2.5-5.5μ) compared to 2.3μ from the SPP correlation. The probe has recently been modified to permit 3-wavelength extinction measurements through the same probe volume used by the PDPA. Successful measurements have been with the combined probe optical techniques. Replacement of some of the aluminum in the propellant with silicon results in the formation of SiO_2 and $A1_6Si_2O_{13}$ at the expense of $A1_2O_3$. Although the total mass of particulate is not changed the average emissivity of the particulate material appears to have been reduced. Two nozzle configurations were utilized to determine the effect of nozzle residence time on the plume particle size distribution since full-scale motors have significantly larger t_{res} than subscale motors. The nozzle residence time was increased from 0.06 ms to 0.127 ms by changing the converging and diverging half-angles. The increased residence time enhanced particle breakup, increasing the % volume with diameters <2μ, but it did not significantly change D_{32} or D_{43}.

1992

IR SIGNATURE AND PARTICULATE BEHAVIOR IN SOLID ROCKET MOTOR PLUMES

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Sponsors: Air Force Phillips Laboratory
National Research Council
Funding: Air force Phillips Laboratory
Naval Postgraduate School

OBJECTIVE: Measure as a function of motor operating conditions and propellant composition the spatial variations of particle size distribution and optical properties and the plume temperature, IR signature and size using a small rocket motor which utilizes aluminized propellant. Compare measured results with SPFIII/R/SIRRMII predictions. Develop a technique for evaluating the effects of motor operating conditions and contaminants/additives on the emissivity of collected particulate as a function of temperature. This is a continuing investigation.

SUMMARY: No one diagnostic technique has been found adequate for measuring the particle size distributions in motors and plumes due to the wide dynamic range and high number density of particles and to the presence of large thermal gradients. A combination of single and ensemble particle analyzers, combined optical/collection probes and SEM analysis of collected samples have been found necessary. Condensed $A1_2O_3$ was found to be the major source of radiation in the 3.5-5μ band in the near-plume and gas phase radiation in the far-plume. Afterburning effects were predominantly confined to reheating of the alumina, which then radiates more than the gaseous species. Highly metallized propellants produced plumes with volume distributed radiation sources and with apparent emissivities predominantly between 0.16-0.19. Particle size distributions were normally bimodal at the nozzle entrance (with 50-90% of the number and <10% of the volume in particles smaller than 1μ) and tri- or quadra-modal in the near plume (with approximately 50% of the volume in particles <1μ). The small particles in the edges of the plume are primarily gamma-alumina with an index of refraction of 1.64. A technique has been developed using rotating tungsten wires in the plume and post-collection examination with an IR microscope to measure the emissivity of plume particulate as a function of temperature. To date, difficulties with convergence have prevented a complete solution of SPFIII/R from being attained for the subscale motor and test conditions employed.

SOLID FUEL RAMJET AND SLURRY FUEL COMBUSTION

D.W. Netzer, Professor of Aeronautics and Astronautics

Sponsor: Naval Air Warfare Center, Weapons Division
Funding: Naval Air Warfare Center, Weapons Division

OBJECTIVE: (1) To complete demonstration of the feasibility of supersonic combustion in solid fuel ramjets, (2) To develop techniques to measure the ignition and combustion characteristics of B/B_4C and to measure the optical properties of plume particulate and (3) to determine the effects of atomizer design on the obtainable particle size distribution and combustion efficiency of gelled, metallized slurry fuels.

SUMMARY: Work was completed on the development and demonstration of a subscale supersonic combustion solid fuel ramjet utilizing plexiglas fuel. The combustor used a mixed supersonic-subsonic flame stabilization region with a small amount of hydrogen pilot gas. Inlet air at M=1.5 was thermally choked in a constant area section and then expanded in a diverging section. Combustor exit Mach numbers were 1.1-1.4 with combustion efficiencies as high as 87% for equivalence ratios between 0.49-0.67. A technique was developed to measure the emissivity of plume particulate in which wires are placed in the plume to collect particles. The wires are then placed under an IR microscope. By accurately measuring the resistance of the electrically heated wire the temperature is determined as the IR image is recorded to yield the emissivity. An initial technique using heated air to heat the wire was unsuccessful. Use of the IR camera to measure the ignition and combustion characteristics of B/B_4C was not accomplished due both to limitations of the IR system temperature range and to a shifting of emphasis to the gelled slurry fuels. Recent IR system upgrades have corrected the high temperature calibration problems. The particle sizes produced by two air-blast and one ultrasonic atomizers were measured using a Malvern particle analyzer. The air-blast atomizers were capable of producing the desired D_{32} of 30-40μ, but only with unacceptably high air pressure drops and high atomizer air-fuel ratios. The ultrasonic atomizer uses more of the available air, but requires very low pressure drops to obtain the desired atomization quality. A combustor was designed and used with center dump, inlet air swirl and axial fuel injection. The air-blast atomizer would not sustain combustion. The ultrasonic atomizer sustained combustion with an efficiency of 76% at an equivalence ratio of 0.78.